ARTIFICIAL PENETRATION PROTOCOL

As used in current regulations, the AOR pertains to the area within which the owner or operator of Class I injection wells must identify all artificial penetrations that penetrate the permitted confining and injection zones. The following is an outline of the steps taken to identify and evaluate artificial penetrations in an AOR.

WELL IDENTIFICATION

Data Sources

A specific and consistent methodology was used to identify all artificial penetrations within the AOR surrounding each Du Pont injection well. Several data sources were utilized to locate pertinent information regarding each artificial penetration. Revised or updated base maps, such as Cambe Geological Services, Zingery Map Co., Tobin Surveys, United States Geological Survey, state regulatory maps, and state highway county maps were utilized to initially identify and establish a general background on the wells in each AOR. State agency files along with state libraries were researched by Agency Information Consultants (AIC) and Banks Information Solutions, Inc., both are located in Austin, Texas for well descriptive documentation. Du Pont internal documents such as old abandoned well studies, well replugging documents, maps, reservoir pressure studies, and well schematics were gathered from the Du Pont Information Center at the Gulf Coast Regional Consulting Office (IC-GCRC) in Beaumont, Texas. Commercial log service companies with regional libraries such as Cambe Geological Services, Incorporated and Petroleum Information were researched for well logs and scout tickets. Additional records data were obtained through oil company sources. Wells lacking data after utilizing the primary resources were researched by contacting original/current operators, lease owners and consulting geologists familiar with that area. Where discrepancies existed among data sources, state form data were considered to be the most accurate.

Well Type

Once identified, the artificial penetrations were then subdivided into wells that are abandoned and wells that are active. An abandoned well is a well where use has been permanently discontinued or is in disrepair such that it cannot be used for its intended purposes. These types of wells include dry holes, abandoned production (oil and gas) wells and injection wells. An active well is a well that is currently operating that includes production and injection (saltwater disposal, enhanced recovery, or other) wells.

WELL DATA EVALUATION AND CRITERIA

Well Status

Each artificial penetration (active/abandoned) was evaluated as to the adequacy of construction and plugging because of the potential for conveying fluid from an injection zone into the overlying USDW. Potential problem wells were identified by failure to meet the criteria outlined below and were subsequently modeled for potential upward migration of fluids in the well bore.

Confining Zone and Injection Zone Penetration

Wells that penetrate the permitted confining zone or injection zone constitute a possible threat to USDWs because of their potential for conveying fluid from the injection zone to an overlying USDW. Available geophysical well logs from the artificial penetrations within the AOR were correlated to determine which of the wells penetrated the confining zone or injection zone. Wells that do not penetrate the confining layers into the site injection interval were considered to be safe (DNP, did not penetrate) from vertical fluid flow and not potential avenues or open conduits for fluid migration.

Rock Types

Discussion has previously been given on the qualities of clays/shales in the Gulf Coast for confinement of injectate by permeation, diffusion, and pressure increase due to injection; that discussion will not be repeated here except to mention that modeling calculations include a large safety factors in unconsolidated rock regions.

Drilling Methods and the Mud Column

The artificial penetrations were classified by their drilling methods (rotary vs. cable). Because boreholes tend to close in unconsolidated rock formations such as the geologically young sands and hydrated shales of the Gulf Coastal Plain, rotary drilling has been the most preferred drilling method. Generally, the drilling mud (typically used with rotary methods) is carefully balanced to keep the caving sands and sloughing shales from entering the borehole. Rotary drilled dry holes (wells without economically recoverable hydrocarbons) without proper plugging records can be assumed to have been left mud filled as a minimum condition because there is no economic reason to recover the drilling mud prior to abandonment (Johnston and Knape, 1986). An exception to this are wells drilled with polymer or oil-based muds which are economical to extract from the well; however, the hole after extraction, is filled with a less expensive bentonite mud. In addition, from examining the mud characteristics taken from well logs for the artificial penetrations in each AOR, none of the wells (with available well logs) lacking plugging records were drilled with these types of mud. Mud characteristics (density, viscosity, type and pH) were obtained from geophysical well logs, state and operator records. Rotary drilled dry holes with protection and/or production casing strings were surveyed for perforations because a well that has been production tested by perforating usually has the drilling mud replaced with a water cushion.

Mud plugs provide an effective barrier to vertical fluid flow in the abandoned well bore as documented previously.

Cable tool drilling is primarily used in consolidated rock formations where the target horizon is shallow. However, this drilling method has not been used in unconsolidated formation regions for the past 50 years. This type of drilling operation does not use drilling fluids for well control; therefore, these types of wells are limited to shallow, low-pressure formations in consolidated or semi-consolidated regions. Fluid left in the hole is typically either water or brine. Cable tool holes are hard to locate because surface casing was usually not cemented and was removed after drilling.

Proper Plugging

An abandoned well is properly plugged if no upward fluid migration or interformational fluid flow occurs as a result of increased reservoir pressure due to injection operations. The Texas Railroad Commission, under Statewide Rule 14, (1967), requires all formations bearing USDW, oil, gas or geothermal resources be protected with type-specific cement plugs and mud-laden fluid. Uncemented areas in the abandoned well bore must be filled with at least 9.5 lb/gal mud. The State of Louisiana has similar requirements. Setting depths for cement plugs are dependent upon the construction of the well and the geological environment. Production or injection wells abandoned with casing left in the hole should be plugged across the base of the lowermost USDW, in each casing string and across all "productive horizons". A productive horizon is defined as any stratum known to contain oil, gas, or geothermal resources.

Wells abandoned with only surface casing should be plugged across the base of the lowermost USDW regardless of casing depth. Where insufficient surface casing is set to protect all USDW and such strata is exposed to the open well bore, a cement plug must be placed across the exposed strata with an additional cement plug set across the surface casing shoe (Texas Railroad Commission, 1986). When sufficient surface casing has been set to protect all USDW strata, a cement plug must be set across the surface casing shoe (Texas Railroad Commission, 1986). Wells abandoned with protection and/or production casing that have been cemented through all USDW strata, all productive horizons must have cement plugs placed inside the casing and centered opposite the base of the deepest USDW stratum (Texas Railroad Commission, 1986). For wells abandoned with protection and/or production casing set back to surface, the casing must be perforated at the depths required to protect all productive horizons and USDW strata with cement placed outside of the casing by squeeze cementing (Texas Railroad Commission, 1986). Wells evaluated to be improperly plugged by the above criteria were considered as "potential problem wells" and were modeled for potential upward migration of fluids.

Proper Well Construction

For the purpose of this study, a properly constructed active or abandoned well is defined as a well where the annulus between the borehole and a casing string has been effectively sealed by cement across the correlated injection interval(s) thereby preventing vertical fluid migration. Wells that were drilled into or through the injection interval and abandoned with protection and/or production casing left in the hole pose potential problems. If cement was not circulated to a depth above the correlated injection zone, only drilling fluid would be present in the annulus. Although the drilling fluid in the annulus would provide the same resistance to vertical fluid migration as a mud plug in the well bore, wells that were constructed improperly were also considered as potential problem wells and modeled for possible vertical fluid migration.

Cement volume calculations were made on each well that has full protection and/or production casing left intact in the well. Only conservative data values were used in the calculations. One inch was added to the borehole diameter and all slurry volumes were calculated using Class H cement with 0% Gel (1.06 ft^3/sack-slurry volume).

Incomplete Records

By far, most of the data on the artificial penetrations in the AOR were obtained from state records. Where public records were missing or virtually nonexistent, private record searches were conducted to locate pertinent data.

ARTIFICIAL PENETRATION MODEL

Summary

Artificial penetrations in the AOR are evaluated to determine if interformational fluid flow can occur in a borehole as a result of a pressure increase above background due to injection. The methods used in this study are similar to those developed and used for many years to model similar cases (Price, 1971; Johnston and Greene, 1979; Barker, 1981; Collins, 1986; Davis, 1986; Johnston and Knape, 1986).

Artifical penetrations which are improperly plugged and/or abandoned are the primary subject of this section. Artificial penetrations which are improperly plugged or for which inadequate plugging records exist are studied to determine that even if improperly abandoned (according to today's standards), increased reservoir pressure does not cause interformational fluid flow.

Artificial penetrations which are properly plugged and abandoned do not need to be modeled because plugging requirements include criteria such that interformational fluid flow cannot occur. Active wells should be constructed properly, thus preventing interformational fluid flow and protecting underground sources of drinking water (USDW). Active wells, including hydrocarbon production wells and salt water disposal wells, which were not properly constructed were also evaluated, based on the mud in the annulus.

Information was obtained to calculate the pressure of the static mud column. If pressure increase due to injection exceeds the static mud column pressure minus original formation pressure, then fluid movement in the mud column could be initiated. Fluid movement could only occur after additional safety factors have been overcome: mud gel strength, borehole closure, and the pressure required to break the gelled mud at the borehole face. Pressure buildup due to injection at an artificial penetration was calculated using the same injection data used in the historical and predicted calculations (calibrated to the historical data) for the injection wells themselves. That model solves the Theis (1935) equation and is modified based on the "leaky aquifer" theory of Hantush and Jacob (1955).

As long as pressure buildup due to injection in each zone remains less than the difference between static mud column pressure and original formation pressure, interformational fluid flow does not occur. If pressure increase due to injection exceeds the allowable buildup, then remedial action would be indicated.

The abandoned well model solves the equations using two different sets of values:

Case 1 - uses allowable values, providing a conservative value for mud column pressure.

Mud column pressure is calculated based on the allowable mud density of 9 lb/gal; no credit for gel strength or borehole closure is used.

Case 2 - uses the actual mud density value and a minimum value for gel strength (20 lb/100 sq ft) if long-string casing was not left in the borehole, providing a realistic value for mud column pressure. No credit for borehole closure is used.

The difference between these two methods provides a safety factor, credited to gel strength pressure and greater static mud column pressure due to higher density mud. A third method of calculating mud column pressure, would be to use actual mud density, a <u>moderate</u> gel strength, and an allowance for borehole closure. Although the third method was not used, the additional pressure due to moderate gel strength and borehole closure would be an added safety factor. In general, mud gel strength was calculated only for boreholes without long-string casing.

The formation pressure increase due to injection was compared to the allowable pressure increase at two times:

1. present day (from beginning of injection in Du Pont waste wells up to recent), and

2. ten years (or more) into the future, of predicted pressures at the abandoned well(s) location based on injection into the waste wells.

The projected injection rate for Du Pont waste wells was based on the maximum permitted injection rate for the wells but limited by the total volume allowable. Thus, the maximum volume of waste which could be injected is being modeled. The injection rate was applied equally to all currently operating Du Pont waste wells, and the same data were used for calculating pressure increases in artificial penetrations for the future. Actual pressures at artificial penetrations in the future should fall below the predicted pressures because the predicted pressures indicate maximum operating conditions. If an abandoned well satisfies current regulations, we can also model whether it will satisfy (current) regulations during continued injection.

Abandoned Well Model Basics

Artificial penetrations that need to be modeled are primarily wells drilled for oil or gas that were improperly abandoned or for which no plugging records exist. These types of abandoned wells are modeled to show whether interformational fluid flow may occur. Artificial penetrations which do not meet the assumptions of the model must be assessed individually.

The model is based on the work of Barker (1981) who derived a procedure for determining the AOR for industrial waste disposal wells and a method of calculating the static mud column pressure in an abandoned well. Barker's calculation results in a minimal AOR. Because his AOR determination was not necessarily conservative, our AOR was determined as the larger of: 1) a 2.0 mile radius around the injection wells [2.5 miles used at Victoria Plant because data were already gathered for the larger area], or 2) the calculated cone of influence. Barker's method of calculating the static mud column pressure in abandoned wells is valid and was used in this study, with slight modifications.

Well bores which were rotary drilled and which did not produce (hydrocarbons or other fluids) can be assumed to have drilling mud filling the well bore because it has no way to escape (Barker, 1981, p. 1; Johnston and Knape, 1986, p. 6). There would have been no economic reason to remove the drilling mud. However, if the mud (e.g., oil-based drilling fluid) was recovered for a different project, the bore hole would be filled with a bentonite-type mud. Completely removing the mud system from the borehole with drill pipe in the hole is taking an unnecessary risk of getting the drill pipe (salvagable material) stuck, because of hole instability and caving (Clark et al., 1987).

The static mud column exerts pressure. For an abandoned well to allow fluid migration through the well bore, the pressures acting on the static mud column (pressure due to injection plus original formation pressure) must be greater than the static mud column pressure.

Static mud column pressure was calculated using the equation:

$$P_s = 0.052 * h * M$$

where:

P_s = pressure of static mud column (psi)
h = depth to uppermost injection zone (ft)
M = mud weight (lb/gal)

and 0.052 is the conversion factor for "oil field" units.

In the conservative case, for upward migration to begin, original formation pressure (P_f) plus the pressure due to injection (P_i) must be greater than the static mud column pressure:

$$P_f + P_i > P_s$$

where:

P_f = original formation pressure (psi)
P_i = formation pressure increase due to injection (psi).

In other words, pressure increase due to injection must be greater than static mud column pressure minus original formation pressure:

$$P_i > P_s - P_f$$

In the second calculation, where gel strength was used, pressure due to gel strength (G) was calculated by:

$$P_g = (0.00333) * G * h / d$$

where:

P_g = pressure due to gel strength (psi)
G = gel strength (20 lb/100 ft^2)
d = bit diameter plus 2 (in.)

and 0.00333 is the conversion factor, such that P_g is in psi.

This margin of safety, P_g, is added to the static mud column pressure and compared to the pressure increase due to injection:

$$P_i > (P_s + P_g) - P_f$$

Naturally, if static mud column pressure is greater than original formation pressure plus pressure due to injection, then the addition of mud gel strength is a further safety factor.

The assumptions of the model and their justifications follow.

Assumptions of the Model

(from Barker (1981) with modifications)

1. The static mud column extends from the base of the abandoned borehole to the surface and has uniform density.

Justification: Segregation of mud components can occur with time, as evidenced upon entering some abandoned well bores. Although little attention has been paid to this aspect, mud density will increase with depth. Even though some settling of the mud may have occurred, a 9 lb/gal mud is a reasonable and conservative value to use as the weight of mud in an abandoned borehole (see Assumption 4). Actual characteristics of the density gradient are unknown and would vary depending on the type of mud, composition, and formation drilled. Mud should have little if any means of escape from the borehole, so a mud column to the surface with a constant density must be assumed to calculate a static mud column pressure.

Individual well records were checked to address the problems of lost circulation zones or a decrease in mud column height from removal of casing for salvage (Johnston and Knape, 1986, p. 7). Identification of either of these problems in an abandoned well would mean modeling that abandoned well with less than a full column of mud or by another method.

Static mud column pressure should vary little from actual pressure because errors in density gradient should offset each other. Gel structure would be expected to increase with depth because of settling of particles through time. The assumption of uniform mud consistency provides the only means of calculating gel strength pressure, because gel strength variations in a mud column are unknown.

2. Abandoned borehole diameter = bit diameter + 2 (in.) in the calculations, where bit refers to the bit size used to drill the hole at the depth of the injection formation.

Justification: Gel strength pressure is inversely proportional to well bore diameter. To compensate for larger surface casing, the effective diameter of the abandoned well bore is the bit diameter used to drill the injection formation plus 2 in. The additional two in. also allows for borehole irregularities (washouts) and will provide a conservative result. The 2-in. allowance prevents having to model the larger diameter surface casing separate from the bit size used to drill the injection zone.

3. Injection pressures will not exceed fracture pressure of the injection formation (a requirement for permitting).

4. Known abandoned wells for which data are unavailable or incomplete are assigned a mud density of 9 lb/gal and the largest bit diameter noted for all wells within a 2.5 mile radius of the injection well(s).

Justification: Mud density of 9 lb/gal is the allowed (and conservative) minimum mud weight (Price, 1972; Collins, 1986; Davis, 1986; Johnson and Knape, 1986; and Alford, 1987). If a lesser mud density were found in other abandoned wells within a 2.5 mile radius of the injection well(s), then the lesser mud density would be used. (A discussion of mud density has been previously made.) Because gel strength is inversely proportional to bit size, the largest bit size provides the most conservative value for gel strength.

5. Abandoned wells were either: 1) dry holes, or 2) production wells with production casing removed <u>and</u> which have records indicating that the borehole was filled with mud at abandonment.

Justification: In either case, mud fills the borehole. In an abandoned dry hole the mud is drilling mud; in an abandoned producer the fluid is usually labeled "heavy mud" or "mud-laden". Mud density may range depending on the regulations in force at time of abandonment.

6. Pressure exerted by the static mud column was calculated at the top of the injection formation.

Justification: Pressure due to injection is assumed to spread throughout the thickness of the zone, and thus be evenly distributed. Calculating the static mud column pressure at the top of the injection formation is conservative because the height of the mud column is a minimum.

7. In calculating mud gel strength, all abandoned wells were drilled with water-based muds (fresh water, salt water, oil-in-water emulsions, and surfactant muds).

Justification: Oil-based drilling muds, and gas and air drilling fluids lack gel strength associated with water-based drilling fluids. Abandoned boreholes drilling with non-water based drilling fluids were not evaluated for gel strength.

8. Gel strength, if used, is assumed to be 20 lb/(100 ft^2).

Justification: Although some work remains to be done on mud gel strength, what is known has been covered in the literature (for example, Barker, 1981; Collins, 1986; Johnston and Knape, 1986). Below is a summary, because currently <u>no credit is given by regulatory agencies for mud gel strength</u>.

Gel strength is the property of mud which acts to suspend drill cuttings in the static mud column when circulation stops. Gel strength forms as a function of: 1) the amount and type of clays in suspension, 2) time, 3) temperature, 4) pressure, 5) pH,a and 6) chemical agents in the mud.

The pressure required to displace the gel can be large, and gel strength may be the main factor in preventing fluid migration within an abandoned well bore (Collins, 1986; Johnston and Knape, 1986).

Barker (1981) determined, under the wide variety of factors contributing to mud gel strength, that 20 lbs/100 ft^2 was a valid conservative (minimum) estimate of mud gel strength. Gray and Darley (1981) determined that approximately 20 lb/100 ft^2 was the lowest possible gel strength that could occur. Thus, 20 lb/100 ft^2 is a reasonable and conservative value for mud gel strength and is used in these calculations where needed.

9. None of the wells which were modeled were properly plugged.

Justification: Pressure calculations are made equitably on static mud columns in abandoned boreholes when all are considered unplugged.

Procedure-Using the Model

1. Locations of all artificial penetrations were digitized from a base map on a Tektronix digitizing tablet linked to a Tektronix T4054 graphics computer.

2. The distance from an artifical penetration to the injection well(s) was then used in the modeling program (see Section 2, Flow and Containment Modeling) to calculate the increase in pressure in an injection interval at the artificial penetration location. The model sums the pressures due to injection from all (if more than one) of the waste wells in an injection interval. Where there is more than one injection interval, pressure due to injection was calculated for each interval modeled. Use of the abandoned well model implies the same assumptions, benefits, and limitations of modeling the waste wells themselves, unless otherwise stated.

3. Information on mud density, bit size, casing size (where applicable) and depth to the uppermost injection sand for an artifical penetration was obtained from the following sources in order of priority:

a. State forms
b. Geophysical log(s), scout cards, other sources of data

Original formation pressure in each injection sand was obtained from one or more of the following (see Flow and Containment Modeling):

a. Bottomhole pressure surveys
b. Pressure modeling of the injection zones
c. Wellhead shutin pressures and density of fluid in the well bore

Original formation pressure at the injection well(s) is corrected for depth in the artificial penetrations by using the gradient determined by original formation pressure at the injection well(s). Original formation pressure in the artificial penetration was calculated at the top of the injection sand.

4. Depth to the uppermost injection sand was determined from geophysical logs. Depths to other injection sand were calculated by adding the distance to the uppermost injection sand to the incremental thicknesses of the injection sands and confining layers based on the pressure modeling parameters.

5. The abandoned well model was run for each injection sand as required using the above noted data.

6. Model outputs include (for each injection sand):

a. Pressure increase above original formation pressure through time, from the beginning of injection at the Du Pont plant through the projection period.

b. Indication of one of the following about the status of the abandoned well with 9 lb/gal mud and no gel strength credit (Case 1):

1) migration of fluids in the abandoned well bore will not occur through the next projected time period of continued waste injection, or

2) migration of fluids in the abandoned well bore does not occur presently, but may occur within the next projected time period, or

3) migration of fluids in the abandoned well bore may be occurring now.

c. Indication of one of the following about the status of the abandoned well with actual mud density and minimum credit for gel strength (Case 2):

1) migration of fluids in the abandoned well bore will not occur through the next projected time period of continued waste injection, or

2) migration of fluids in the abandoned well bore does not occur presently, but may occur within the next projected time period, or

3) migration of fluids in the abandoned well bore may be occurring now.

Results of Model

Further investigation or remedial action is indicated if output from the model indicates that there is fluid migration occurring in a borehole.

SAMPLE CALCULATIONS OF STATIC MUD COLUMN PRESSURE

Hypothetical case:

a. original formation pressure 1750 psi at 4000 ft BLS (injection zone)

b. actual mud weight in abandoned well = 10.4 lb/gal

c. minimum gel strength of 20 lb/100 ft^2

d. borehole radius 9 7/8 in. (add 2 in. for rugosity and irregularities = 11 7/8 in.)

<u>Case 1</u>:

Static mud column pressure assuming 9 lb/gal mud (conservative value) in borehole and <u>not</u> allowing for gel strength:

(0.052) x (4000 ft) x (9 lb/gal) = 1872 psi

1872 psi - 1750 psi (original pres.) = 122 psi buildup allowed

Case 2:

Static mud column pressure using actual mud weight and not allowing for gel strength:

$(0.052) \times (4000 \text{ ft}) \times (10.4 \text{ lb/gal}) = 2163 \text{ psi}$

2163 psi - 1750 psi (original pres.) = 413 psi buildup allowed

Case 3:

Static mud column pressure using actual mud weight and allowing for minimum gel strength (20 lb/100 ft^2):

$$[(0.052) \times (4000 \text{ ft}) \times (10.4 \text{ lb/gal})] + [(0.00333) \times (20) \times (4000 \text{ ft}) / (11.875)] = 2185 \text{ psi}$$

2185 psi - 1750 psi (original pres.) = 435 psi buildup allowed

The results of these sample calculations are summarized:

BUILDUP ALLOWED AT ABANDONED WELL

Case 1	-	9 lb/gal mud, no gel strength	122 psi
Case 2	-	actual mud wt.; no gel strength	413 psi
Case 3	-	actual mud wt.; min. gel strength	435 psi

Obviously, calculations with actual mud weight, with or without gel strength credit, would allow a much higher buildup of pressure than allowing only 9 lb/gal mud.

REFERENCES

Alford, S. E., 1987, Conoco Senior Drilling Engineer (drilling mud specialist), Houston, Texas.

Barker, S. E., 1981, Determining the area of review for Industrial Waste Disposal Wells: Master's Thesis, The University of Texas at Austin, Austin, Texas, p. 146, [0110853].

Clark, J. E., Howard, M. R., and Sparks, D. K., 1987, Factors That Can Cause Abandoned Wells to Leak as Verified by Case Histories from Class II Injection, Texas Railroad Commission Files: UIPC Class II Injection Well Symposium, [0111159].

Collins, R. E., 1986, Technical Basis for Area of Review: Prepared for Chemical Manufacturers Association, Reference 80-160-000-4, [0110859].

Davis, K. E., 1986, Factors Effecting the Area of Review for Hazardous Waste Disposal Wells in Proceedings of the International Symposium on Subsurface Injection of Liquid Wastes: Dublin, Ohio, National Water Well Association, p. 148-194.

Gray, G. R., and Darley, H. C. H., cited in Collins, R. E., 1986, Technical Basis for Area of Review: Prepared for Chemical Manufacturers Association, Reference 80-160-000-4, [0110859].

Hantush, M. S., and Jacob, C. E., 1955, Nonsteady Radial Flow in an Infinite Leaky Aquifer: Transactions of the American Geophysical Union, v. 36, no. 1, p. 95-100.

Johnston, O. C. and Greene, C. J., 1979, Investigation of Artificial Penetrations in the Vicinity of Subsurface Disposal Wells-Technical Report: Texas Department of Water Resources.

Johnston, O. C., and Knape, B. K., 1986, Pressure Effects of the Static Mud Column in Abandoned Wells: Texas Water Commission LP 86-06, p. 99, [0110880].

Price, W. H., 1971, The Determination of Maximum Injection Pressure for Effluent Disposal Wells-Houston, Texas Area: Master's Thesis, The University of Texas at Austin, Austin, Texas, p. 84.

Theis, C. V., 1935, The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground Water Storage: Transactions of the American Geophysical Union, August, 1935, p. 519-524.

Appendix 4-7

The Determination of Maximum Injection Pressure for Effluent Disposal Wells - Houston, Texas Area (Price, 1971)

See Original 1990 Sabine River Works No Migration Petition Section 4, Area of Review, Appendix 4-7

Appendix 4-8
Area of Review Determination
(Texas Water Commission, 1977)

See Original 1990 Sabine River Works No Migration Petition
Section 4, Area of Review, Appendix 4-8

Appendix 4-9

Investigation of Artificial Penetrations in the Vicinity of Subsurface Disposal Wells (Johnston and Greene, 1979)

See Original 1990 Sabine River Works No Migration Petition Section 4, Area of Review, Appendix 4-9

Appendix 4-10

Determining the Area of Review
for Industrial Waste Disposal Wells
(Barker, 1981)

See Original 1990 Sabine River Works No Migration Petition
Section 4, Area of Review, Appendix 4-10

Appendix 4-11

Pressure Effects of the Static Mud Column in Abandoned Wells (Johnston and Knape, 1986)

See Original 1990 Sabine River Works No Migration Petition Section 4, Area of Review, Appendix 4-11

Appendix 4-12

Factors Affecting the Area of Review
for Hazardous Waste Disposal Wells
(Davis, 1986)

See Original 1990 Sabine River Works No Migration Petition
Section 4, Area of Review, Appendix 4-12

Appendix 4-13

Technical Basis for Area of Review
(Collins, 1986)

See Original 1990 Sabine River Works No Migration Petition
Section 4, Area of Review, Appendix 4-13

Appendix 4-14

Confining Layer Study - Supplemental Report
(Warner et al., 1986)

See Original 1990 Sabine River Works No Migration Petition
Section 4, Area of Review, Appendix 4-14

Appendix 4-15

Abandoned Oil and Gas Industry
Wells and Their Environmental Implications
(Warner, 1988)

See Original 1990 Sabine River Works No Migration Petition
Section 4, Area of Review, Appendix 4-15

Appendix 4-16

Factors That Can Cause Abandoned Wells to Leak as Verified by Case Histories from Class II Injection, Texas Railroad Commission Files (Clark et al., 1987)

See Original 1990 Sabine River Works No Migration Petition Section 4, Area of Review, Appendix 4-16

Appendix 4-17

Test Results for the Nora Schulze Well No. 2
(Pearce, 1989)

See Original 1990 Sabine River Works No Migration Petition
Section 4, Area of Review, Appendix 4-17

Appendix 4-18

Report of Examination of Mud Conditions
(AIC, 1988)

See Original 1990 Sabine River Works No Migration Petition
Section 4, Area of Review, Appendix 4-18

Appendix 4-19

Drilling Mud as a Hydraulic Seal
in Abandoned Well Bores
(Collins, 1989)

See Original 1990 Sabine River Works No Migration Petition
Section 4, Area of Review, Appendix 4-19

Appendix 4-20

Borehole Closure Test Well Demonstration
(Clark et al., 1991)

GULF COAST BOREHOLE CLOSURE TEST WELL
ORANGEFIELD, TEXAS

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ABSTRACT

A borehole closure protocol for a Gulf Coast site near Orangefield, Texas was developed by Du Pont. These procedures were based largely upon recommendations provided by EPA Region 6 and created a borehole closure test to demonstrate that, under a worst case scenario, any artificial penetration will seal naturally. The borehole closure test successfully demonstrated natural sealing. Within one week of setting the screen, tubing and pressure transducers in the borehole, testing confirmed the absence of upward movement of fluid from the test sand. The documentation for the absence of upward movement included: 1) Schlumberger Water Flow Log* and 2) the absence of pressure response on the upper transducer located outside the tubing and inside the casing. Testing was conducted in accordance using specified procedures, with pressure testing conducted at even higher pressures to allow an added margin of confidence. The borehole closure test provides a significant additional margin of confidence that there will be no migration of hazardous constituents from the injection zone for as long as the waste remains hazardous.

INTRODUCTION

The borehole closure study was conducted to address concerns associated with the movement of injected fluids toward the Orange Salt Dome from the injection wells operated at the Du Pont Sabine River Works. The borehole closure test well (Orange Petroleum #35 Hagar) is located on the east bank of Cow Bayou on the eastern flank of Orange Salt Dome, east-southeast of the town of Orangefield, Texas (see Figure 1). The study was performed in response to EPA's request for additional information sufficient to demonstrate that, even assuming a worst-case basis that wastes might migrate across the faults at Orange Salt Dome, there would be no migration of hazardous constituents from the injection zone upward through artificial penetrations.

* Mark of Schlumberger

Previous studies (Johnston and Greene, 1979; Davis, 1986; Johnston and Knappe 1986; Clark et al., 1987) have reported qualitatively that wells drilled in unconsolidated (soft) rock, such as the Gulf Coastal Plain in Texas, experience natural borehole closure. This study was developed by Du Pont for a quantitative analysis on natural borehole closure and was based upon recommendations provided by EPA. The worst-case scenario developed for this study included: 1) a test interval within the injection zone consisting of a thin injection sand overlain by a thick, sand-free shale; 2) an open borehole with a diameter equal to the largest hole diameter expected to be encountered among the abandoned wells at Orange Salt Dome, 3) a mud program designed in accordance with drilling practices in general use at the time the abandoned boreholes in question were drilled (1919), and 4) actual testing with a 9.0 lb/gal brine since this is the worst-case condition for abandoned holes without plugging records. The test protocol provided that the test would be successful if, when a 100 psi pressure increase was applied, a Water Flow Log or oxygen activation (OA) log run at stations above the injection sand interval showed no upward channeling and an upper pressure transducer showed no pressure buildup.

The maximum calculated value for potential pressure increase at this site is <80 psi, which includes all possible sources of pressure increase: 1) maximum density contrast between natural formation fluid and the injected waste (0.075) and 2) a worst-case density drive if the plume extended from the plant to the dome (maximum dip 2400 feet). More likely, the long-term effect of buoyancy occurs where the plume has drifted from the plant to the dome and the number of feet of dip is considerably less, only 300 feet. In the latter case, the pressure due to buoyancy would be <10 psi. Thus, testing the borehole closure well to 100 psi increase is an extremely conservative approach.

If an artificial penetration had been abandoned with casing in place, the casing would corrode, thus 'exposing' whatever was in the borehole to the formation. This corrosion information was based on conservative data from Orange Salt Dome artificial penetration data and National Association of Corrosion Engineers data (Graver, 1985). Using a maximum casing wall thickness of 0.557 inch for 8 5/8-inch casing and a conservative corrosion rate of 20 mils per year, the casing would corrode in 28 years, which is long before waste reaches Orange Salt Dome in approximately 5,000 years. This value is consistent with casing corrosion data available from producing wells in the Orangefield area.

The geologic formations present at depths of 2000 ft to 8000 ft consist mainly of middle to upper Miocene sands, with lower Oligocene Anahuac Shale, and Frio sands at greater depth (see Figure 2). Tertiary sands and shales were deposited in a series of stacked progradational wedges, which dip and ultimately thicken toward the Gulf of Mexico. The lower Miocene Lagarto and the middle Miocene Oakville Formation are both characterized by very thick, fine to very fine grained sands, silts and shales deposited in a fluvial and deltaic environment. The regional geologic structural setting is one characteristic of salt tectonics, with salt dome intrusions, minor salt ridges and deep synclines. Orange Salt Dome is a piercement type salt dome (top of salt approximately 7000 feet) where considerable quantities of hydrocarbons have been produced since 1919.

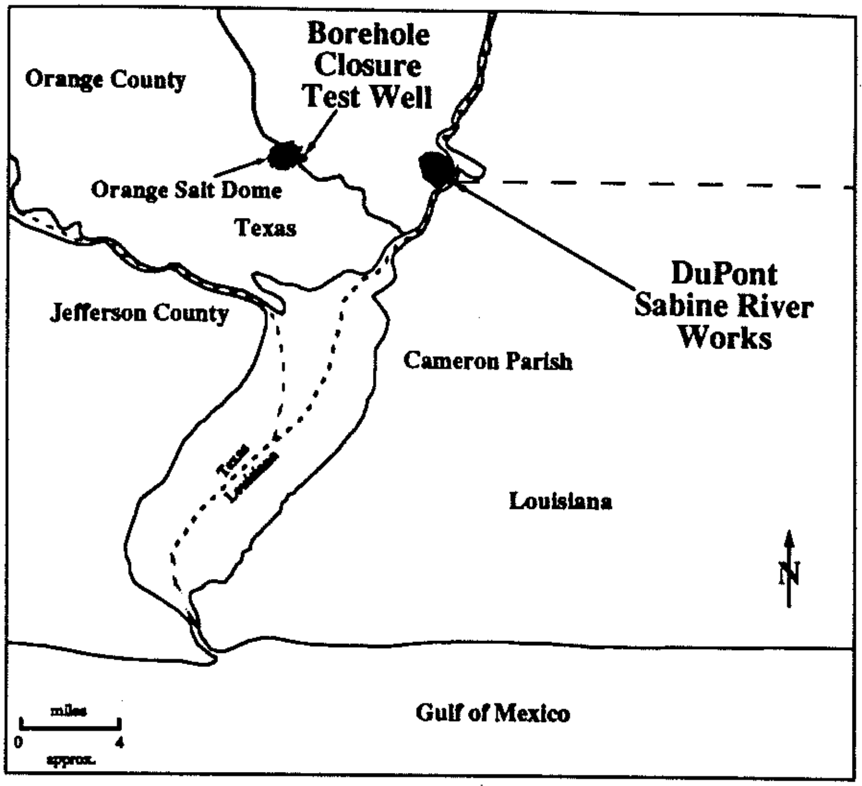

Figure 1 : Geographic Location Map of the Sabine River Works and the Borehole Closure Test Well

Period	*Epoch*	*Stage or Group*	*Formation*
QUATERNARY	HOLOCENE	Undifferentiated	
		12,000 YA	
	PLEISTOCENE	Houston L. Wisconsin	Beaumont
		Wisconsin E. Wisconsin	
		Sangamon L. Illinoian	
		Pre-Sangamon E. Illinoian	Lissie
		Yarmouth Kansan	
		Aftonian Nebraskan	Willis
		2.8 MYA	
TERTIARY	PLIOCENE	Citronelle Group	Goliad
		5.2 MYA	
	MIOCENE	Fleming Group	Lagarto
			Oakville
		24 MYA	
	OLIGOCENE	Catahoula Group	Anahuac
		Vicksburg Group	Vicksburg
		37 MYA	

Figure 2: Stratigraphic Column for Eastern Gulf Coast. Adapted from Jackson and Galloway, 1984.

PROCEDURES

Following evaluation and analysis of the mudlog, lithology samples, openhole logs, and visual examination of sidewall cores obtained from the test well, several sand and shale zones were determined to be potential candidates for the test interval. Using the protocol developed by Du Pont with recommendations from the EPA, the criteria for test interval selection called for a thin clean injection sand, overlain by a thick sand-free shale within the injection zone. The injection sand selected contains 30 net feet of clean sand (2932 feet - 2962 feet) with 88 net feet of clean shale (2838 feet - 2926 feet). The casing was set at 2838 feet into the shale of the test interval. This graphic is presented in the well construction schematic using the electric log as a base (see Figure 3).

Analysis of two sidewall cores for particle size distribution from the injection sand was an important factor in determining the screen size. Sidewall core plugs from 2937 feet and 2945 feet were analyzed for porosity, permeability and lithology. Silt and clay particle analysis indicated a median grain size of 0.0046 inches. Using this information, the size of the screen assembly selected was 0.006 inches, the best gauge of screen that would most closely fit the particle size of the formation for a natural completion. Porosity within the test sand ranges from 29.6 to 31.8% (neutron-density log porosity ranges from 29 to 31%), with permeabilities on the order of 900 to 1400 millidarcies (md).

In order to satisfy a further worst case condition, Du Pont, at EPA's request investigated and evaluated electric logs of representative wells located within the confines of the 10,000-year waste plume. These artificial penetrations were evaluated for continuity of shale overlying the test sand. The shale of the test interval was demonstrated to be continuous and correlatable in its areal extent across the highest point of Orange Salt Dome. In addition, this test interval was at a shallow depth which minimized the geologic overburden pressures and the forces causing shale creep into the open wellbore.

BOREHOLE CLOSURE TESTING

OVERVIEW

Borehole closure testing started April 21, 1991 and was completed May 4, 1991. This sequence of borehole closure testing consisted of the following general steps:

Step 1

With drill bit and drill string still in hole, condition 9.7 lbs/gal mud in the open borehole. See Figure 4 for a schematic diagram depicting the mud circulation in the open borehole.

Step 2

Pulled drill string into casing and displaced mud with 9.1 lbs/gal filtered brine near the casing shoe to clean up the well bore casing and fluids prior to running the screen, transducers, and tubing assembly. (See Figure 5).

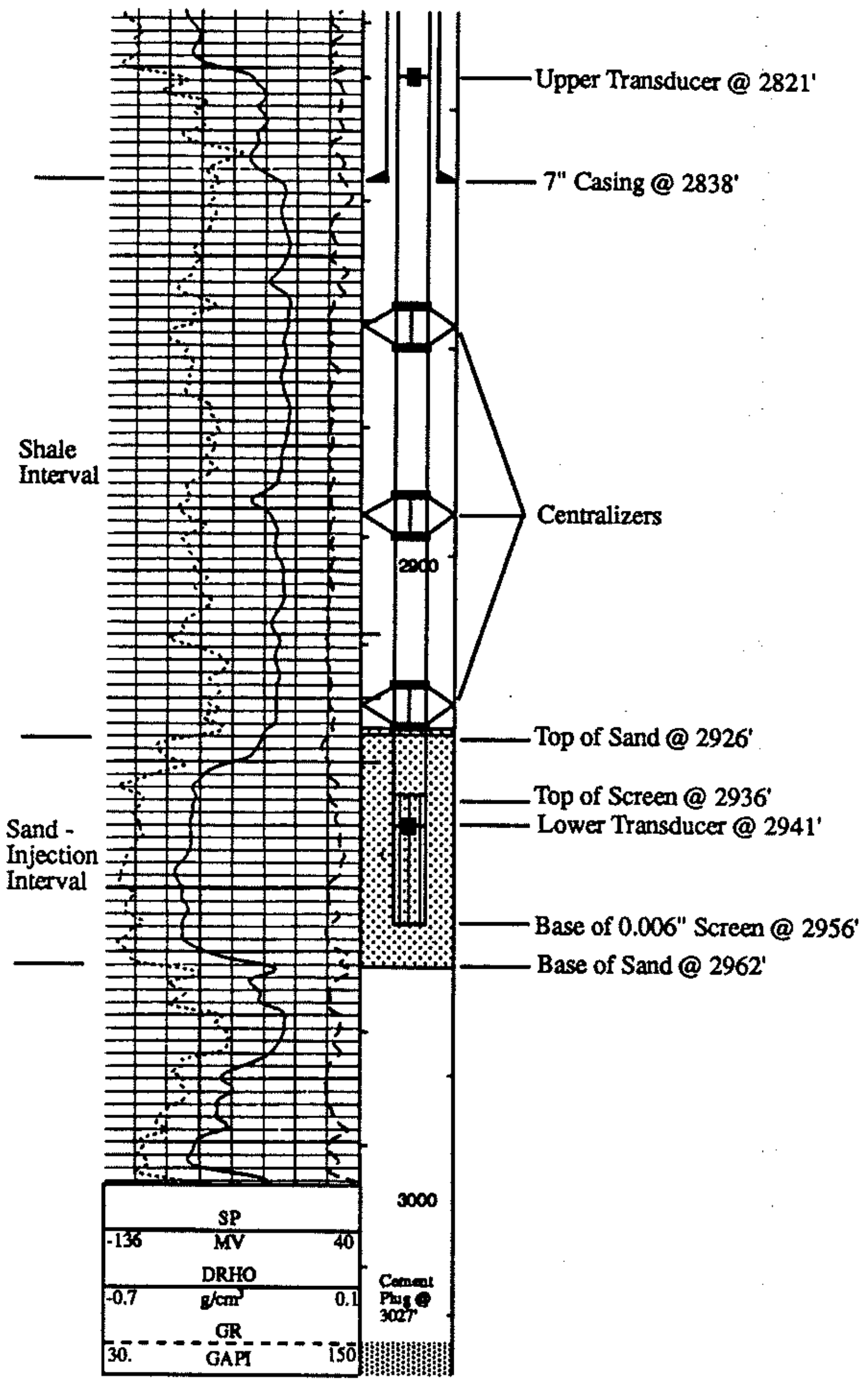

Figure 3: Borehole Closure Test Interval

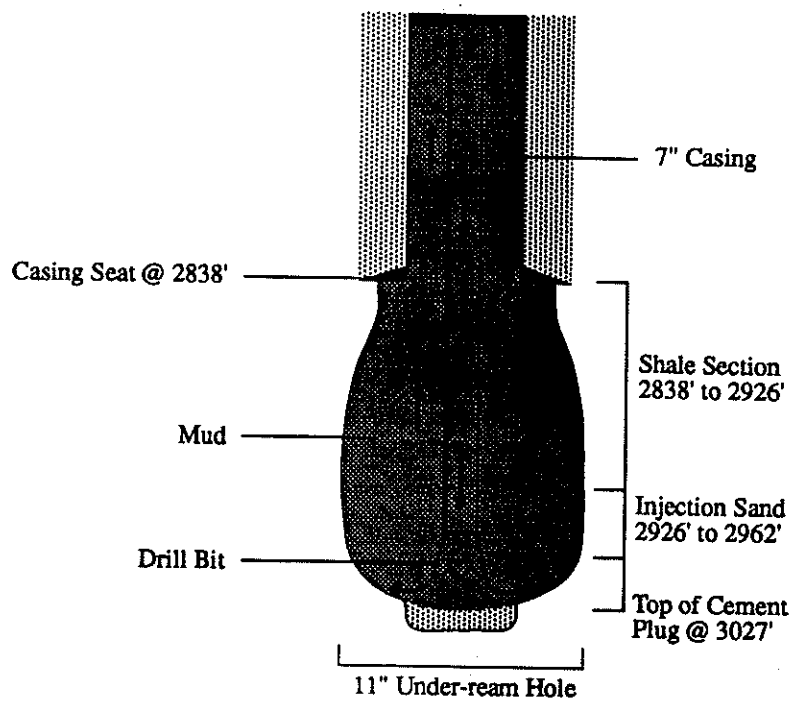

Figure 4: Mud Circulation

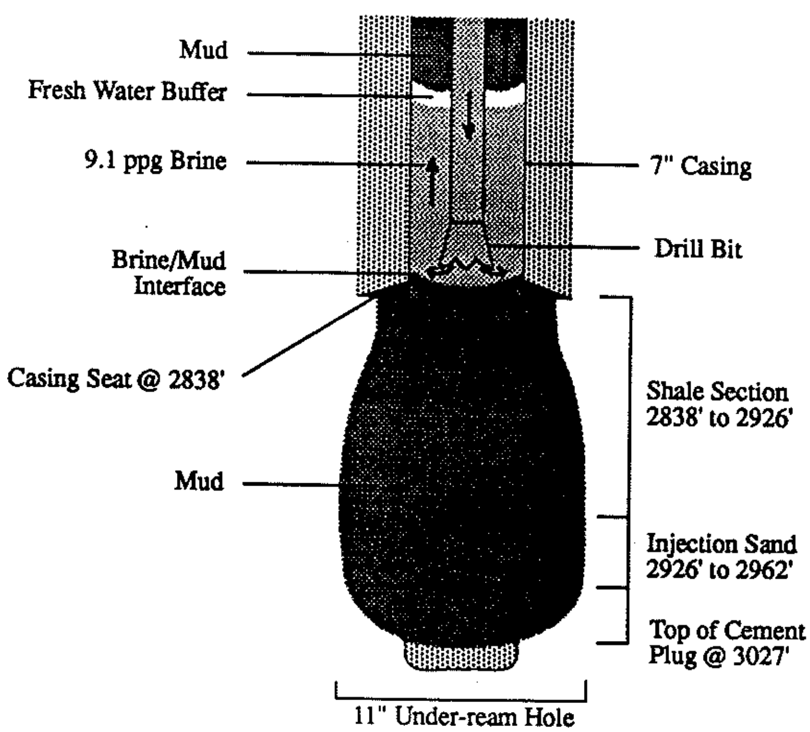

Figure 5: Mud Displacement with Brine Near Casing Shoe

Step 3

After the well bore casing was displaced with 9.1 lbs/gal filtered brine, the screen assembly, transducers, and tubing were placed near the bottom of the casing shoe. A transducer test was conducted to ensure that the electrical equipment was operating properly before running the screen assembly in the open borehole. In addition, filtered brine was pumped at various flow rates up to a maximum of 8.5 barrels per minute (bbl/min) to determine the friction loss in the screen section next to the lower transducer. See Figure 6, Transducer Test at Bottom of Casing.

Step 4

After the completion of the transducer test, the screen assembly was placed through the injection sand from 2936 feet to 2956 feet. Once this was completed, displacement of the remaining 9.7 lbs/gal mud with 9.1 lbs/gal filtered brine in the open borehole began immediately. See Figure 7, Screen Placement.

Step 5

A total of 401 barrels of 9.1 lbs/gal filtered brine was circulated to clean up the well bore. Mud returns from the open well bore occurred on the surface after pumping 85 barrels of brine down the injection tubing. The well bore discharge line started to clean up after 200 barrels of brine were pumped into the injection tubing. An additional 200 barrels of brine were pumped at decreasing flow rates until the discharge line indicated clean fluids in the return. See Figure 8, Brine Circulation After Mud Displacement.

Step 6

After displacement of the mud from the well bore with the 401 barrels of brine, the well was shut-in. See Figure 9, showing well shut-in with brine and recording falloff pressures.

Step 7

After waiting one week, during which time the formation pressure achieved equilibrium, a pre-injection slug test was conducted. The pre-injection slug test verified that the screen was open and that the injection formation was responding properly. Next, a Halliburton pump truck was placed on location along with a control valve to regulate the low flow rates anticipated for the pressure build-up testing. The initial injection testing indicated that borehole closure had occurred and Schlumberger was called out to run their Water Flow Log. Schlumberger performed the logging runs at various pressure rates and depths which indicated that there was no upward channeling of fluid and that borehole closure had indeed occurred. See Figure 10 for a schematic depicting Water Flow Log and Pressure Testing with Brine Injection.

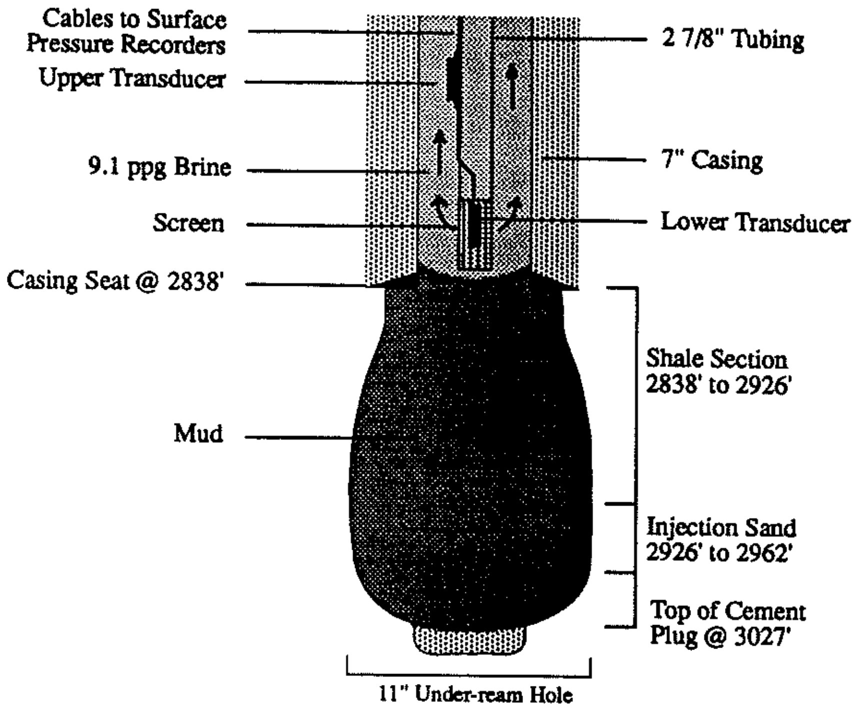

Figure 6: Transducer Test at Bottom of Casing

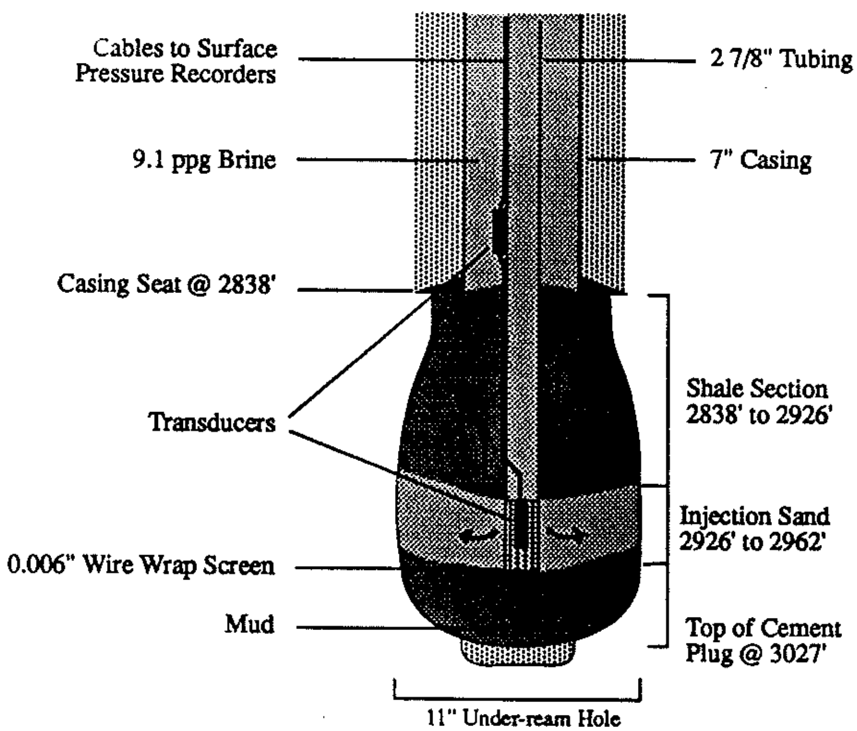

Figure 7: Screen Placement

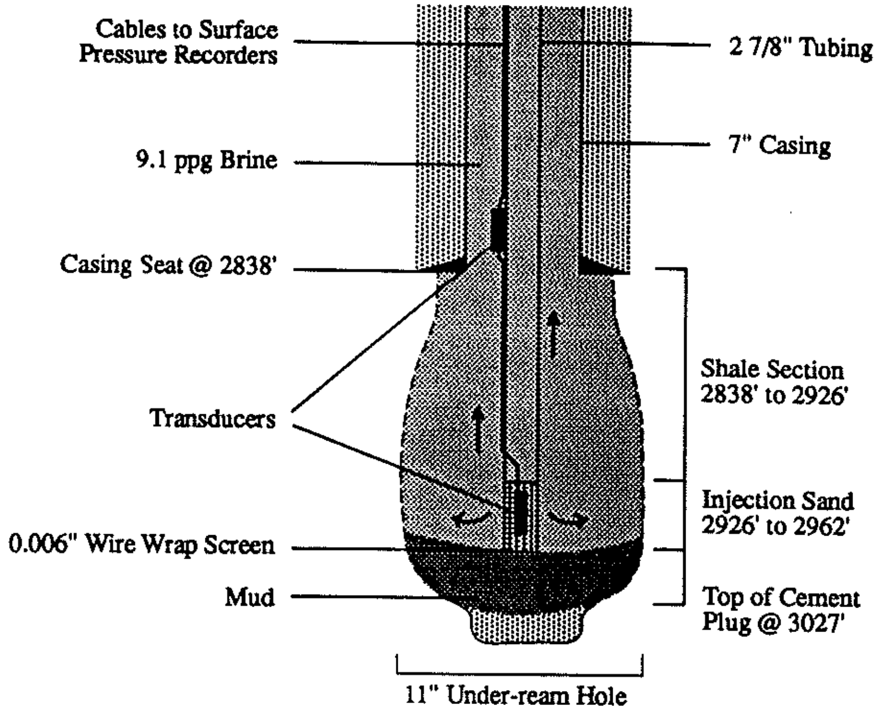

Figure 8: Brine Circulation After Mud Displacement

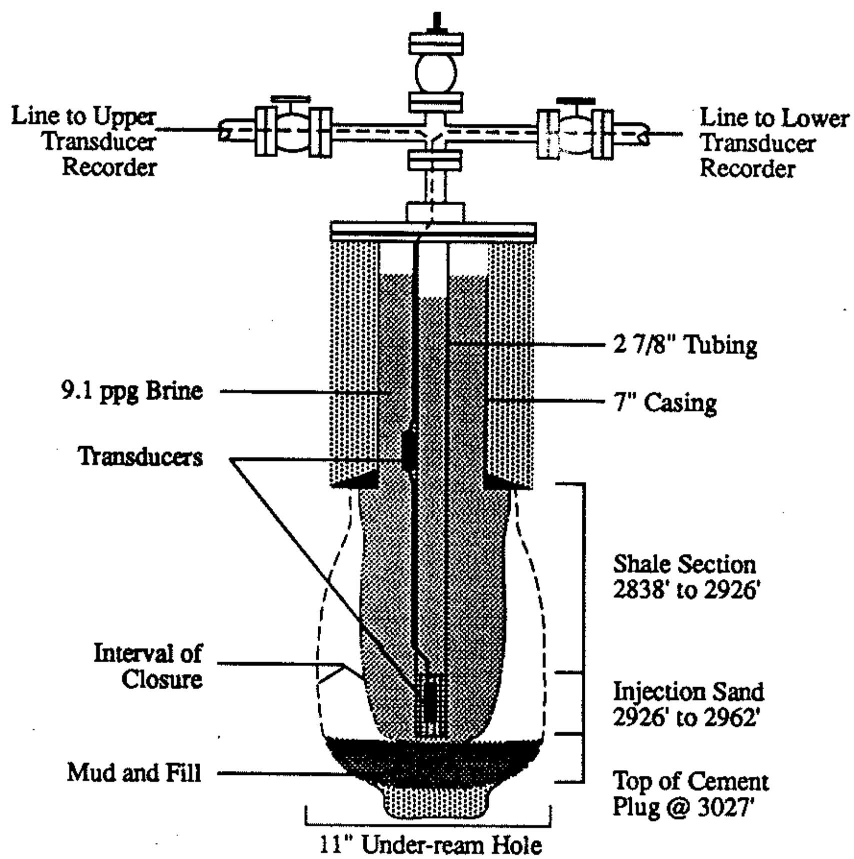

Figure 9: Shut Well In and Record Pressures

DETAILS FROM CONDITIONING HOLE TO MUD DISPLACEMENT

After the open borehole was conditioned with 9.7 lbs/gal mud the drill bit and pipe were tripped out of the open borehole and placed inside the casing above the casing shoe. Drilling mud inside the casing was displaced with 9.1 lbs/gal filtered brine near the casing shoe to limit mud invasion of the well screen. Once the mud was displaced from the casing and clear brine returns appeared on the surface, brine injection stopped, and the drill bit and pipe were tripped out of the casing. The lower transducer was installed inside the well screen, approximately four feet from the top of the screen openings. An upper transducer was attached to the outside of the 2 7/8 inch tubing approximately 120 feet above the lower transducer. Next, the screen, lower and upper pressure transducers, and the tubing assembly were lowered inside the well bore to a depth near the casing shoe.

A transducer test was conducted April 23, 1991, inside the well casing prior to running the screen assembly inside the open borehole. This tested both transducers under static and dynamic conditions and ensured that all electrical equipment (transducers) was functioning properly. The lower transducer at 2758 feet had a static pressure reading of 1305 psi (see Figure 11). Therefore, the pressure transducer was operating correctly by measuring the hydrostatic pressure of the 9.1 lbs/gal brine (0.052 x 2758 ft x 9.1 lbs/gal = 1305 psi). The upper transducer at 2638 feet (see Figure 12 also was operating properly by recording the static pressure of 1248 psi (0.052 x 2638 ft x 9.1 lbs/gal = 1248 psi). Another method verifying that the transducers were recording accurately is to state that (1305 psi - 1248 psi)/(0.052 x 9.1) = 120 feet, the distance that the transducers are separated.

A dynamic test was conducted after obtaining the static pressure measurements from the lower and upper transducers (see Figures 11 and 12). This test was conducted at several production rates (1.5 to 8.5 bbl/min) per EPA Region 6 requests to determine the pressure drop or friction loss across the screen assembly. The screen assembly consists of a wire-wrapped (0.006 inch) re-inforced tubing with a total of 120 holes per foot of screen (3/8 inch diameter per hole). This type of construction minimizes friction losses in the screen assembly. The dynamic test conducted near the casing shoe revealed that the pressure loss would be less than 12 psi for 2 bbl/min flow rate in the screen assembly. The upper transducer reflected a 10 psi buildup for this same time period showing that the 12 psi loss is not all attributed to friction loss inside the screen. The injection test itself was conducted at less than 0.5 bbl/min.

DETAILS FROM MUD DISPLACEMENT TO END OF TESTING

The pressures recorded from mud displacement to the end of testing for the lower and upper transducers are presented in Figures 13 and 14, respectively. Once the screen was properly placed, the 9.7 lbs/gal mud in the open borehole was displaced immediately with 9.1 lbs/gal filtered brine. Details for each of the major historical sequences comprising the borehole closure demonstration are described below.

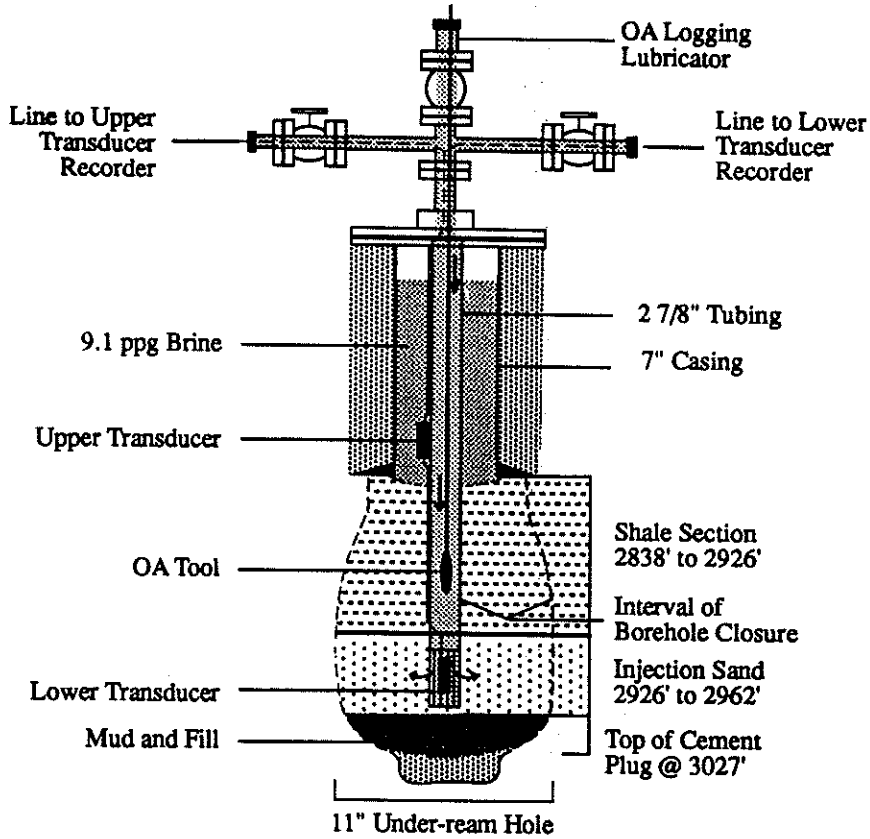

Figure 10: Water Flow Log and Pressure Testing with Brine Injection

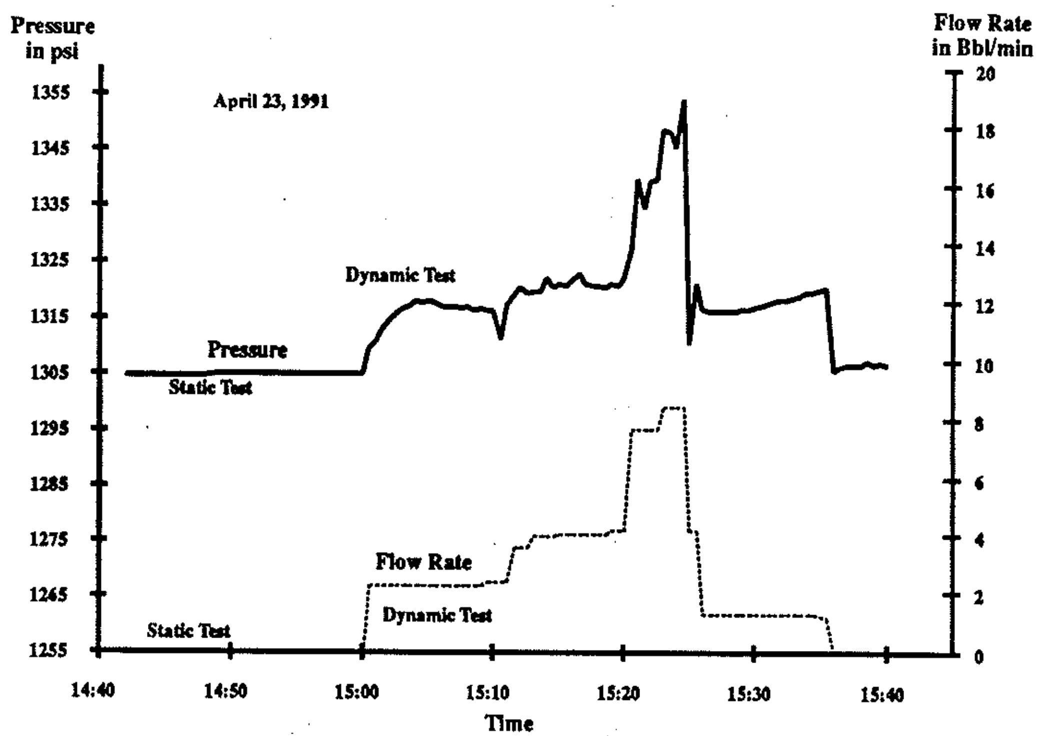

Figure 11: Transducer Test Near Casing Shoe With Lower Transducer at 2758 feet

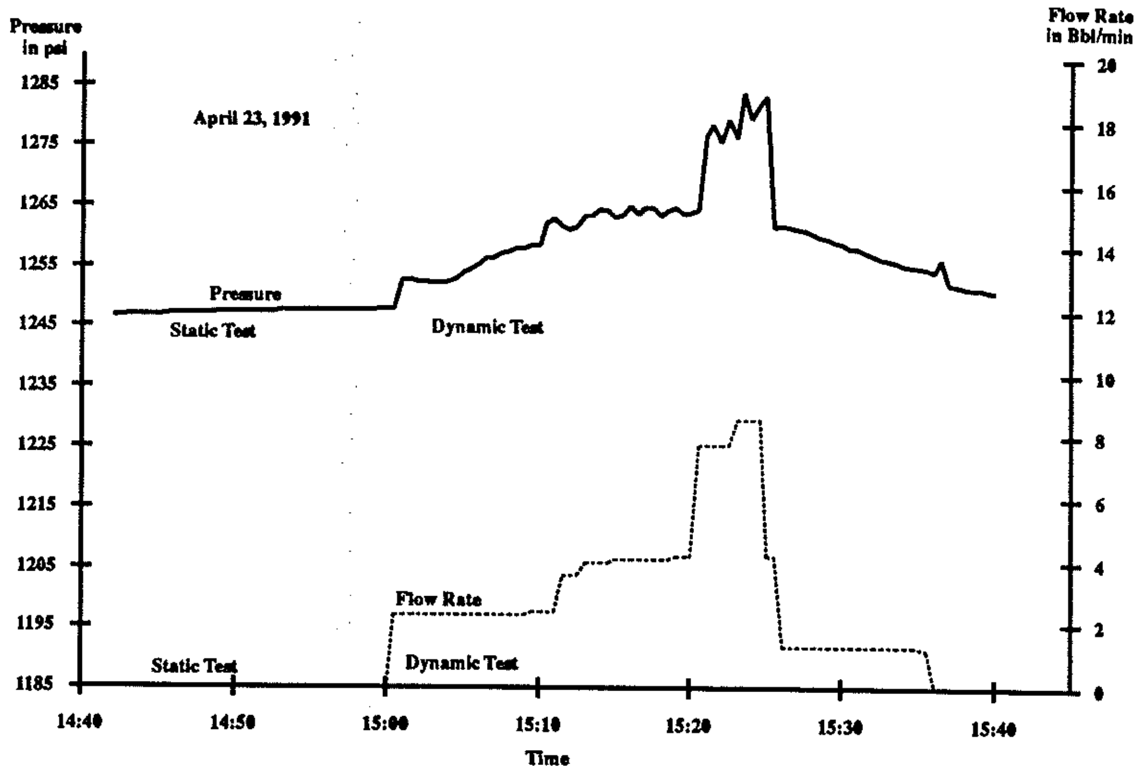

Figure 12: Transducer Test Near Casing Shoe With Upper Transducer at 2638 feet

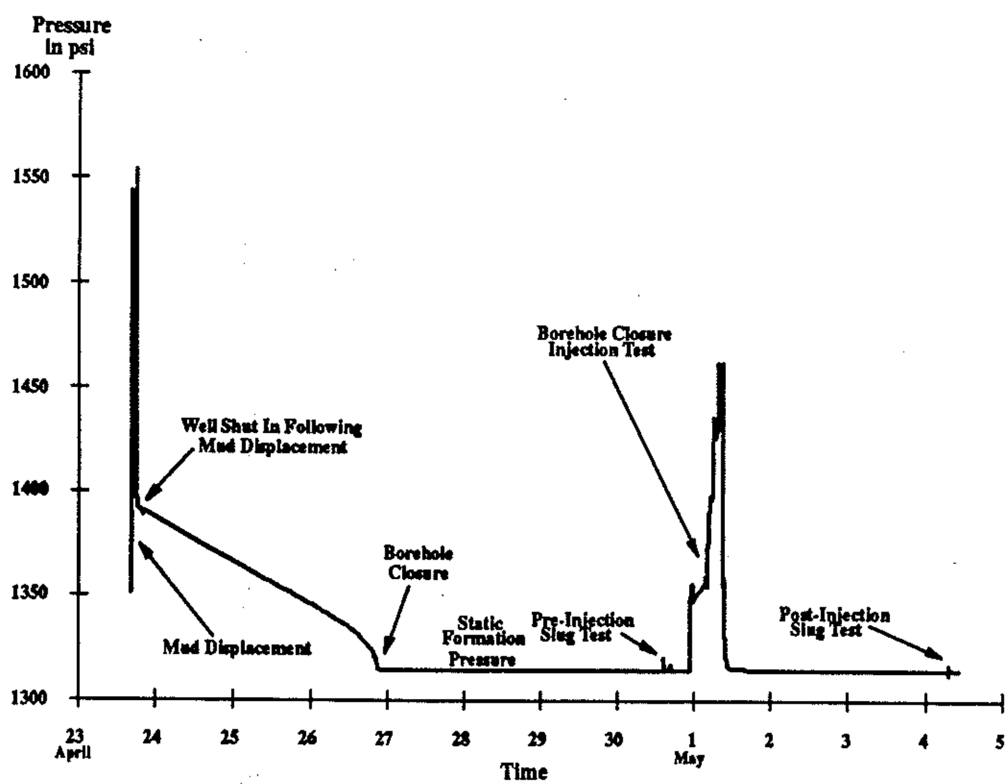

Figure 13: Lower Transducer Data From Mud Displacement to End of Testing

A total of 401 bbl of 9.1 lbs/gal filtered brine was pumped through the injection tubing with returns to the surface. Figure 15 shows that the mud displacement caused an increase in the pressure of the upper transducer at 2821 feet until mud was displaced from the well bore. After pumping 85 bbl of brine the drilling mud appeared on the surface and the discharge line was switched from the brine tank to the mud tank. The discharge rate near the end of the test was reduced gradually to prevent sudden well surges which could cause the well screen to fill with sand.

The final brine returns were clean with only minute traces of gumbo shale. After the mud displacement sequence, the well bore was shut-in and pressures were recorded. Recovery data (see Figure 16) show a slow pressure decline. Pressure data indicate that borehole closure occurred within 3 to 4 days after the well was shut-in following mud displacement. The screened interval or lower transducer reflects static formation pressure (1314 psi) within this time frame. Also, the upper transducer (inside the well casing) indicates a pressure-time slope change within this same time period. Only minor pressure changes occurred after this time period for the upper transducer, and this would be expected because the brine could still react with the shale below the casing shoe. Calculation of different fluid levels from the upper and lower transducers also show isolation of the two zones.

According to procedures agreed upon by Du Pont and EPA Region 6, it was Du Pont's decision to determine what duration to leave the well bore shut-in. Du Pont notifed EPA Region 6 after placement of the screen assembly that it would leave the well in a static condition for a time period of approximately one week before starting the injection test.

A pre-injection slug test (see Figure 17) consisting of two separate series of five slugs (each slug equaled 2.5 gallons of brine) was performed April 30, 1991, one week after shut in. The purpose of this test was threefold: 1) to determine if the screen was open and operating properly, 2) to determine the volume of water that might be needed to conduct a pressure buildup in the formation, and 3) to determine if there was a pressure response in the upper transducer. As shown in Figure 17, the fall-off curves in the lower transducer indicated that the screen was open (i.e., not filled with sand). There was no pressure response in the upper transducer from the slug testing, indicating that the two transducers were indeed isolated. Finally, the testing revealed that a pump truck would be required to control the low flow rate of brine injection. In addition, because the required flow rates could be lower than a truck could pump (less than 20 gpm), a valve was installed to regulate even lower flow rates. Halliburton computer flow monitoring and pumping services, Otis filters and brine fluids were ordered to the location for the borehole closure injection test.

Early testing data showed that the lower transducer was recording pressure buildup with no pressure increase observed in the upper transducer. The flow rate was increased slightly from 16 gpm to 22 gpm to obtain a 40 psi buildup. At this point, before reaching 50 psi of formation buildup, Schlumberger was called to run a Water Flow Log which would check for upward fluid channeling. Schlumberger was contacted for logging services at 23:30 hours on April 30, 1991. In order to conserve brine the flow rate was reduced to 16 gpm. The upper transducer continued to show no pressure change from injection, except for minor temperature anomalies associated

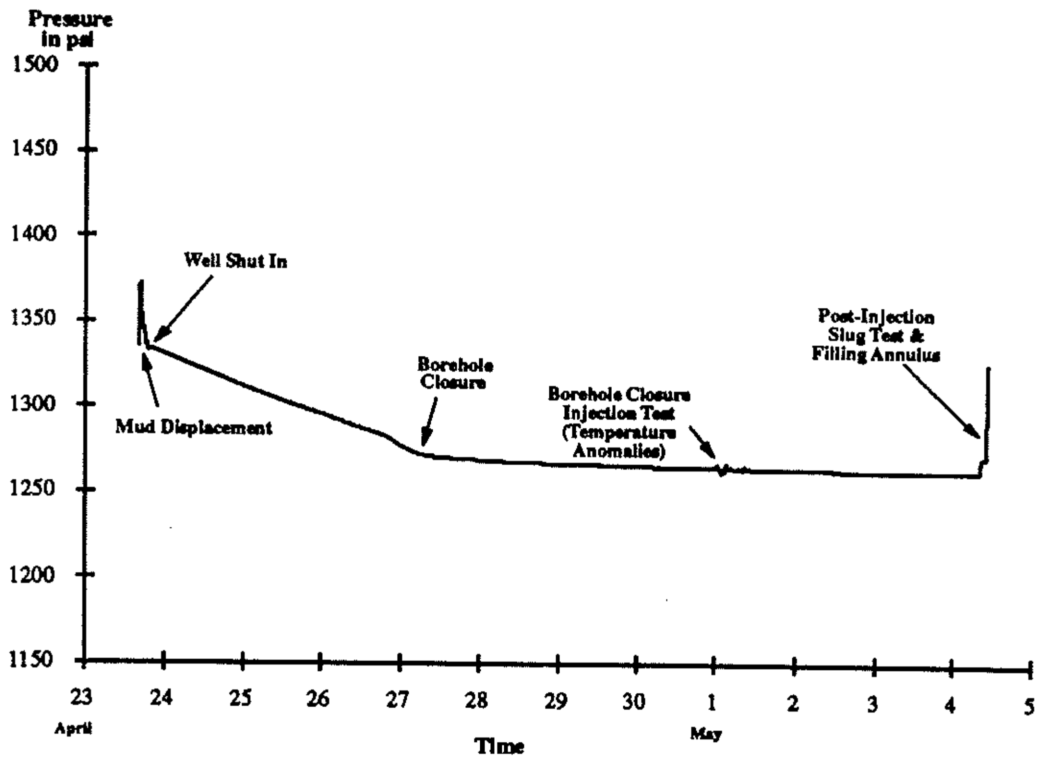

Figure 14: Upper Transducer Data from Mud Displacement to End of Testing

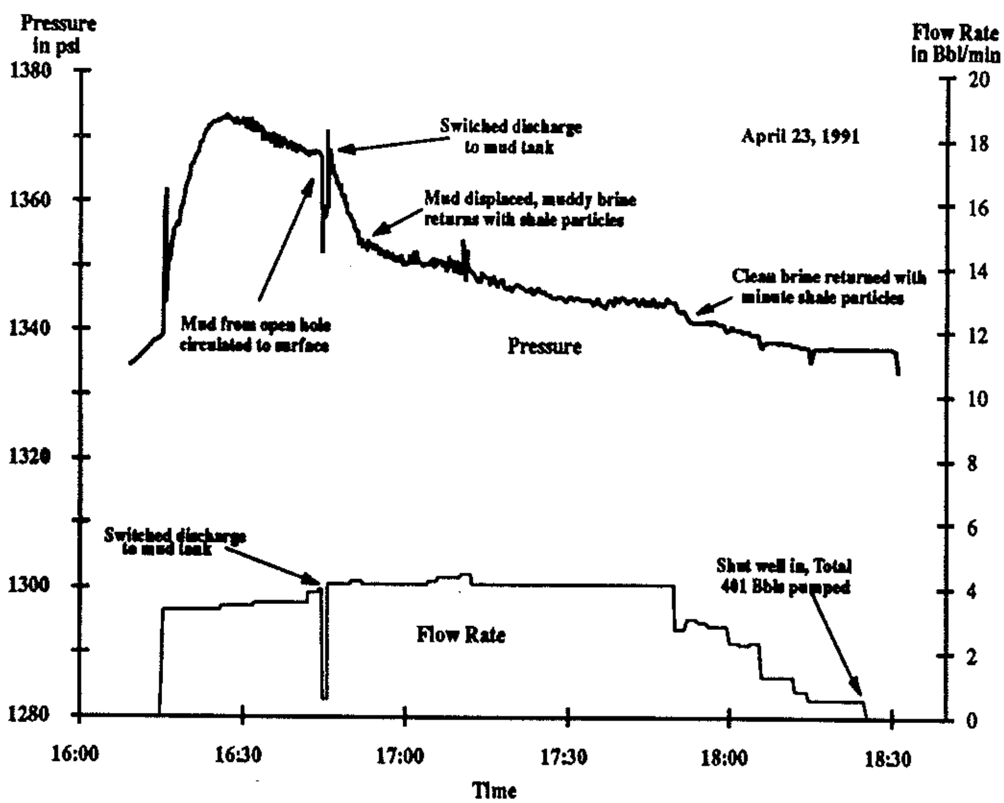

Figure 15: Mud Displacement With Upper Transducer at 2821 feet

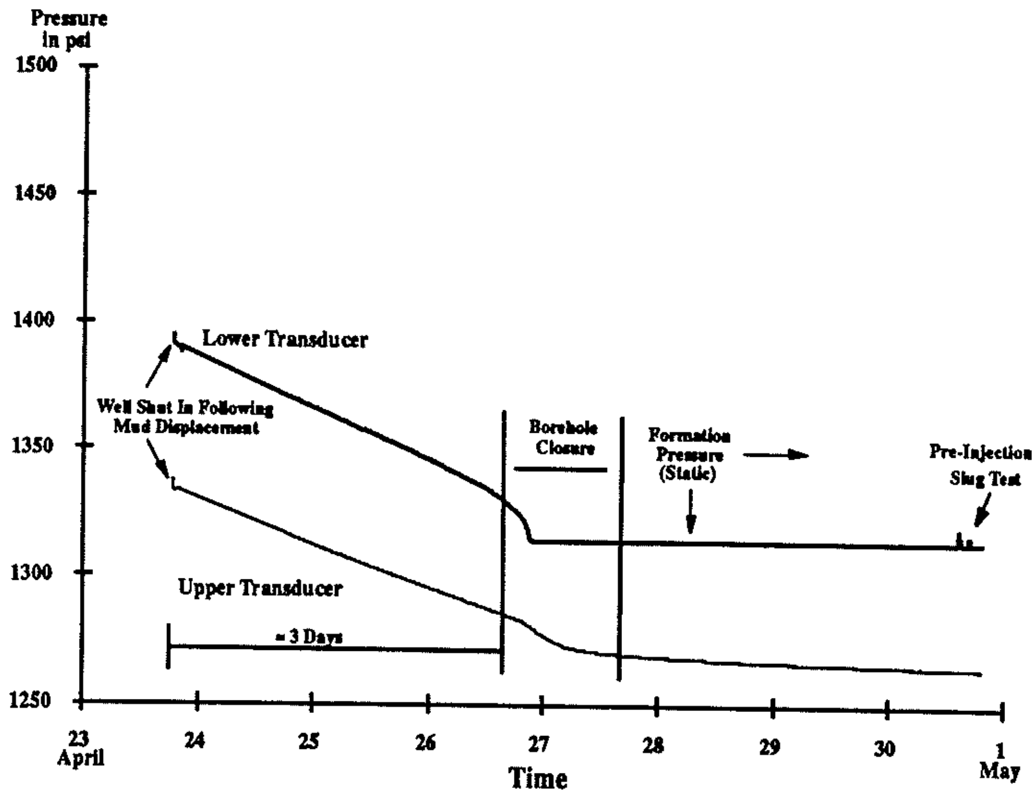

Figure 16: Recovery Following Mud Displacement

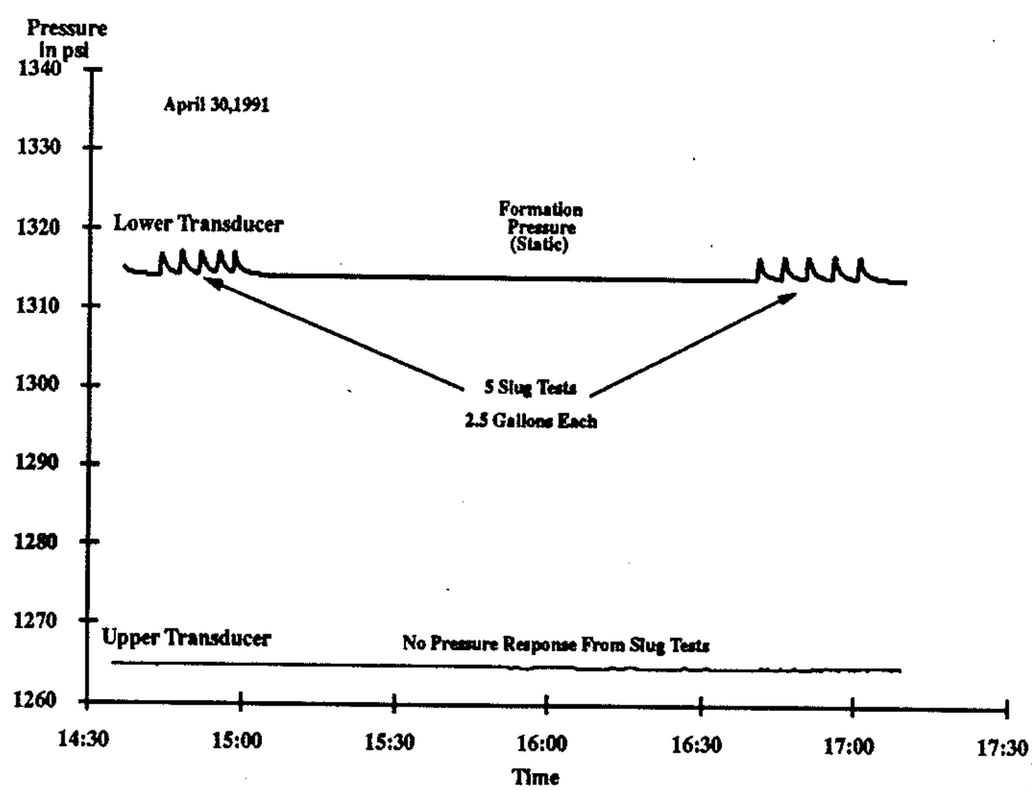

Figure 17: Pre-Injection Slug Test

with the cooling effect of injection fluids. Figure 18 presents an overview of the borehole closure injection test for the upper and lower transducer and a plot of fluid temperature. Figure 19 is an enlargement of fluid injection temperatures and the upper transducer pressures. This graph demonstrates the minute temperature anomalies associated with the cooling of fluids in the well bore.

Figure 20 is a plot of transducer pressure and flow rates during the borehole closure testing. The Water Flow Log was conducted within the tubing under pressure control conditions at 90 psi, 110 psi, and 140 psi above static formation pressure and at stations within the overlying shale interval at approximately 25 feet, 50 feet, and 75 feet above the test injection sand. In an attempt to maintain constant formation pressure during each OA log run, the flow rates were reduced. Flow rates were increased to obtain the next formation pressure OA log run; however, the formation pressures continued to increase and the flow rates were further reduced (see Figure 20) to maintain a consistent formation pressure increase over static. Both the upper transducer and the OA logging indicate no upward channeling of fluid. The final run of the Water Flow Log (OA) showed no upward movement of fluids even as shallow as 25 feet above the injection sand.

Du Pont conducted a post-injection test prior to cutting the transducer lines to the surface recorders and pulling the tubing and screen assembly. The purpose of this test was to verify that the lower transducer was still working and that the upper transducer would respond to fluid placed in the annulus. Figure 21 shows that the upper transducer was working and that there was no bleed-off of pressure into the lower transducer. This was the case even when the annulus was filled to the surface with fluid. This also demonstrated well closure and sealing of the shale section between the injection sand and the casing. Table 1 shows x-ray diffraction data for the test interval and indicates that the shale section consists of expandable smectite clay layers.

EPA was not only interested in whether natural borehole closure occurred, but also if a rate of borehole closure could be quantified. During this test, natural borehole closure was demonstrated, and a rate of borehole closure was 'quantified'.

CONCLUSION

The borehole closure test was designed and constructed according to EPA criteria for a worst-case scenario. This worst-case scenario assumes that hazardous waste migrates across a non-sealing fault and encounters an artificial penetration of maximum borehole diameter filled with 9.0 lb/gal brine. The test interval selected was a thin sand overlain by a thick, sand-free shale.

The test sand was pressured up to the pressure specified and greater with no upward fluid flow or channeling detected during oxygen activation logging station, even with a minimum of 25 feet of shale. Recorded pressures indicate no channeling of fluid because of the pressure differential between the two sensors. Results of the test provide conclusive evidence that a borehole closes naturally, even under a worst-case scenario.

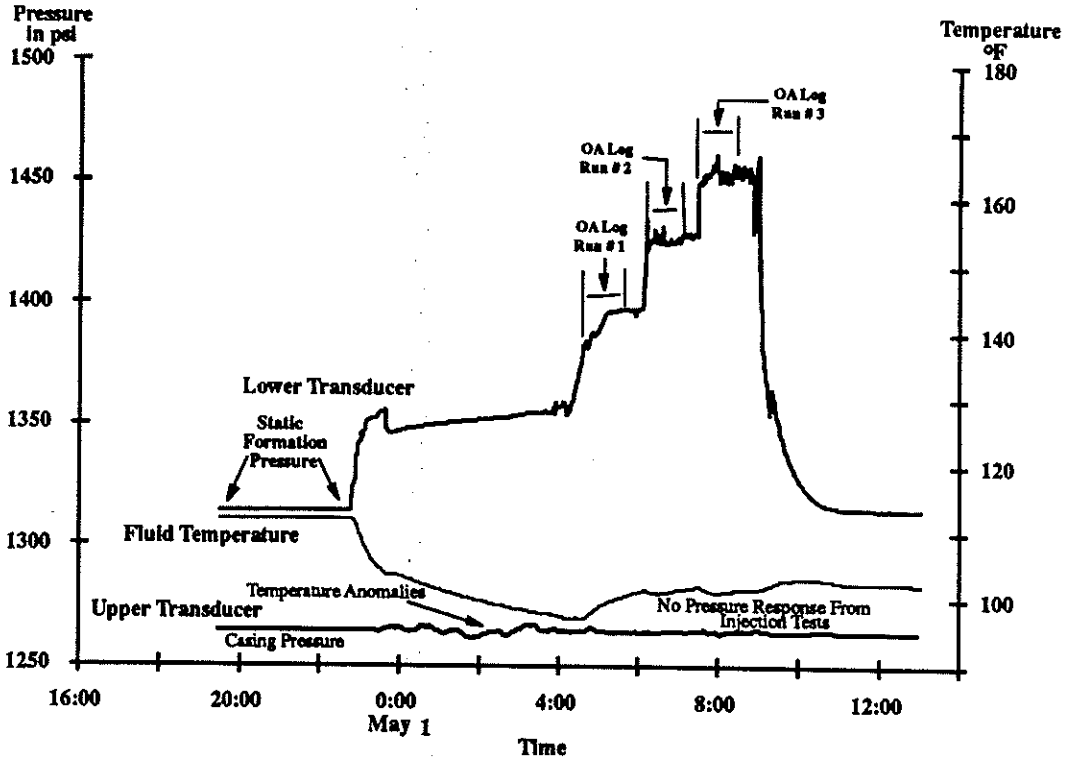

Figure 18: Borehole Closure Injection Test Upper and Lower Transducers- Pressure & Temperature

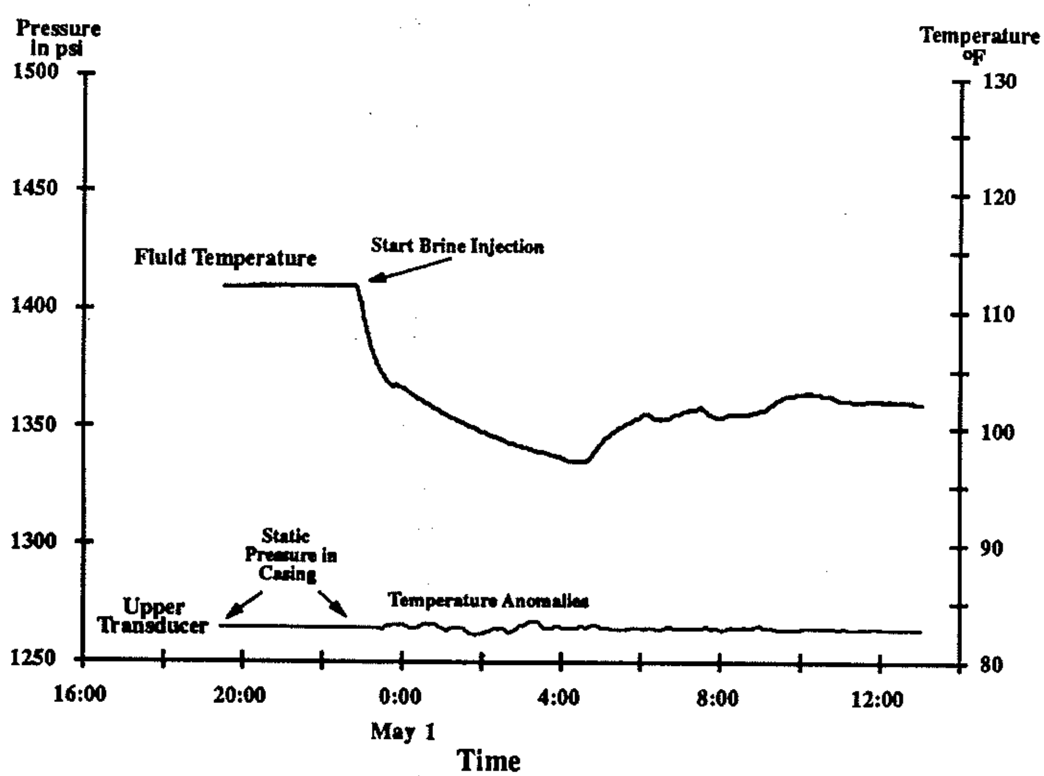

Figure 19: Borehole Closure Injection Test-Fluid Temperature Anomalies

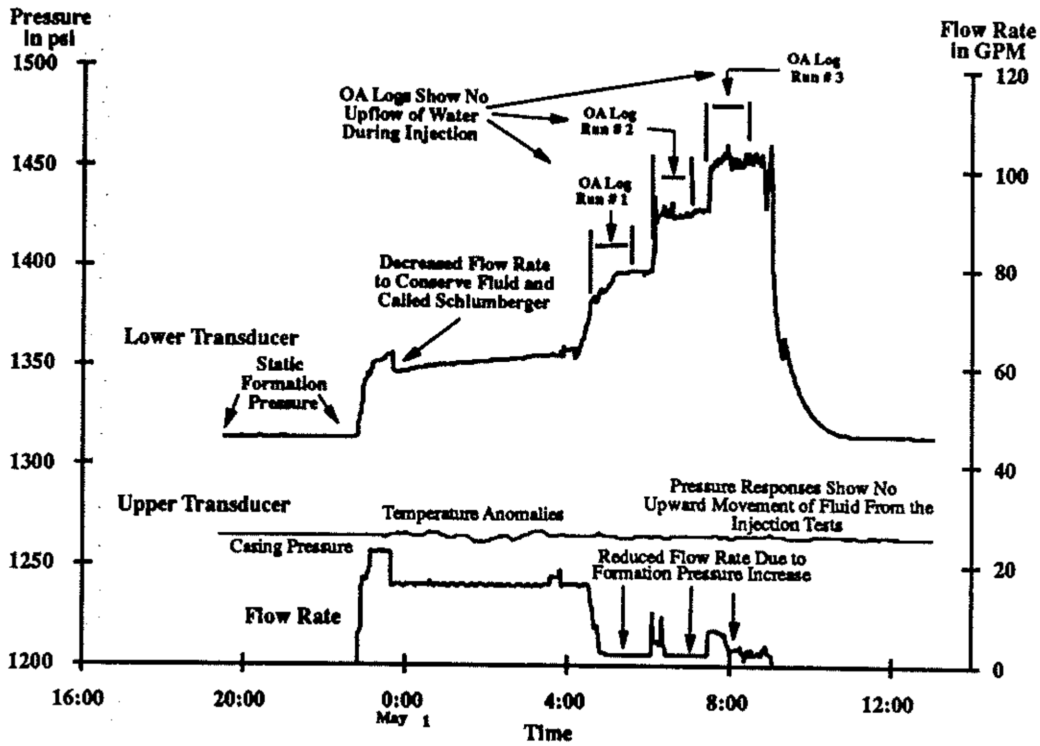

Figure 20: Borehole Closure Injection Test-Upper and Lower Transducer Pressure and Flow Rate

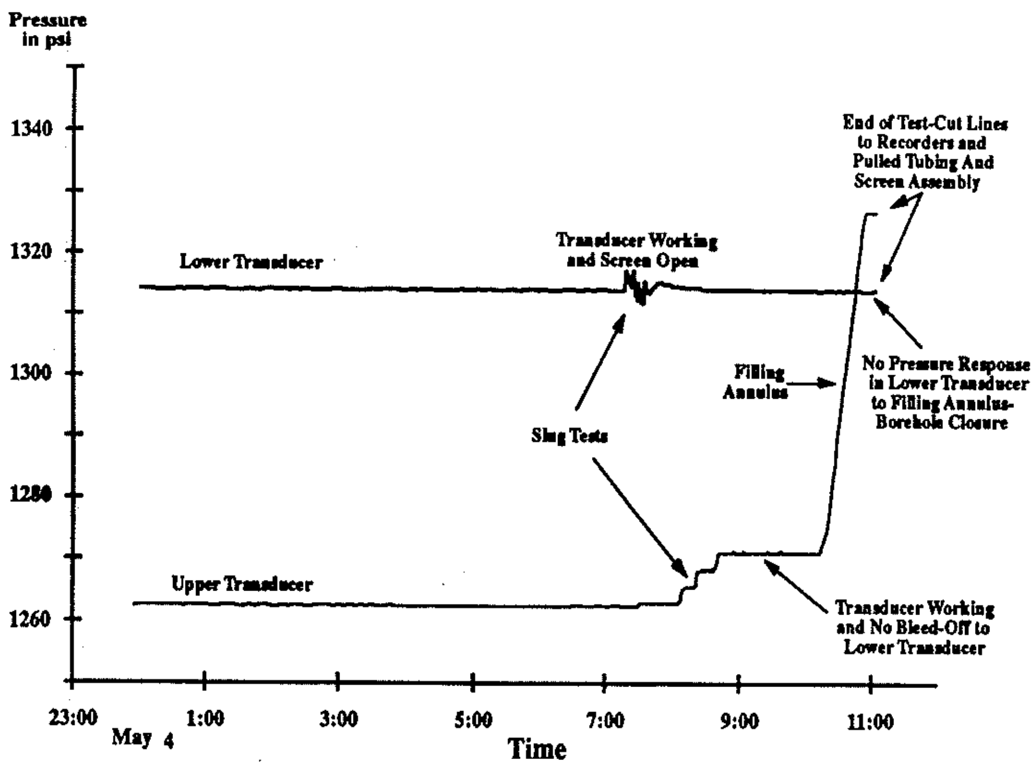

Figure 21: Post-Injection Transducer Testing

Table I

Du Pont Borehole Closure
Orange Petroleum No. 35 Hager

X-RAY DIFFRACTION (XRD) DATA
(Weight Percent)

Depth:	2737	2900	2925	2940	3110
		BULK MINERALOGY (Calculated)*			
Quartz	25	41	30	77	23
Total Feldspar	02	06	04	15	04
Plagioclase	01	03	02	06	02
K-Feldspar	01	03	02	09	02
Calcite	02	08	20	02	14
Dolomite	—	—	01	—	trace
Fe-Dolomite	—	trace	—	trace	—
Siderite	—	—	—	trace	—
Pyrite	04	01	08	—	trace
Total Clay	67	44	37	06	59
	100%	100%	100%	100%	100%
		Relative Clay Abundance (Normalized to 100%)			
Kaolinite	05	05	09	08	05
Chlorite	02	02	02	02	03
Illite	05	06	08	04	08
Mixed-Layer Illite/Smectite**	88(80)	87(85)	81(85)	86(85)	84(75)
	100%	100%	100%	100%	100%

* Bulk mineralogy is calculated from sand/silt-size and clay-size XRD data.
** Numbers in ( ) are percent expandable smectite interlayers in mixed layer clays.

ACKNOWLEDGMENTS

We acknowledge Joe Kordzi and Ronnie Crossland, EPA, who critiqued the test procedures and submitted recommendations which were incorporated into the borehole closure protocol. We thank Marion Miller for providing drilling engineering services at the borehole closure well.

REFERENCES

Clark, J. E., Howard, M. R., Sparks, D. K. 1987, Factors That Can Cause Abandoned Wells To Leak As Verified By Case Histories From Class II Injection, Texas Railroad Commission Files: International Symposium On Subsurface Injection Of Oilfield Brines, Underground Injection Practices Council, Oklahoma City, OK, p. 166-223.

Davis, K. E., 1986, Factors Effecting the Area of Review for Hazardus Waste Disposal Wells: Proceedings of the International Symposium on Subsurface Injection of Liquid Wastes, National Water Well Association, Dublin, OH, p. 148-194.

Graver, D. L. (Ed.), 1985, Corrosion Data Survey - Metals Section (Sixth Edition): Houston, National Association of Corrosion Engineers, p. 7.

Jackson, M. P. A., and Galloway, W. E., 1984, Structural and Depositional Styles of Gulf Coast Tertiary Continental Margins: Application to Hydrocarbon Exploration: American Association of Petroleum Geologists, Continuing Education Course Note Series No. 25, 226 p.

Johnston, O., and Green, C. J., 1979, Investigation of Artificial Penetrations in the Vicinity of Subsurface Disposal Wells: Texas Department of Water Resources.

Johnston, O. C., and Knape, B. K., 1986, Pressure Effects of the Static Mud Column in Abandoned Wells: Texas Water Commission LP86-06, 99 p.

BIOGRAPHICAL SKETCHES

James E. Clark holds a B.S. in geology (1972) from Auburn University and an M.S. in geophysical sciences (1977) from Georgia Institute of Technology. As a geohydrologist with Law Engineering Testing Co., he worked on suitability studies of salt domes as repositories for nuclear waste. He is a consultant with Du Pont's (E. I. du Pont de Nemours & Co., Inc., Engineering Department, P. O. Box 3269, Beaumont, TX 77704) solid waste and geological engineering group and is active in permitting and evaluation of disposal wells.

Philip W. Papadeas received his B.S. degree in geology from the University of New Hampshire (1978). As a field engineer with Schlumberger he was active both offshore and onshore Texas, and later served as petroleum geologist for Omega International, Inc., generating oil and gas exploration prospects. In 1988, he joined Du Pont's geological engineering group in Beaumont, Texas as a consulting geologist responsible for geological and hydrological modeling and evaluation of UIC Class I disposal wells.

Diane K. Sparks received her B.S. degree (1977) in geology and her M.S. degree (1978) in geology from Bowling Green State University. She was a petroleum geologist with Amoco Production Company and Helmerich and Payne, Inc. Sparks is a consulting geologist (P. O. Box 7103, Beaumont, TX 77726) and since 1986 has consulted for the Engineering Service Division of Du Pont, in evaluation of UIC Class I disposal wells and fluid migration studies.

Ronney R. McGowen received his B.S. degree (1989) in geology from Lamar University in Beaumont, Texas. He is currently working toward his M.S. degree in geology at Texas A & M University. He has worked in the drilling industry for 9 years as a driller and rig superintendent in western Oklahoma and the Texas Gulf Coast. He is now working as a contract geologist for the Engineering Service Division of Du Pont, in evaluation of Class I disposal wells.